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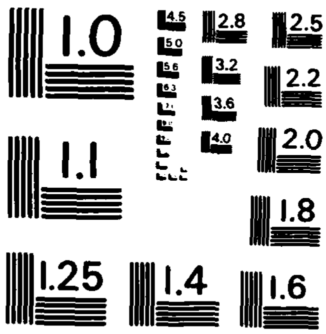
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MULTIPLE IGNITION, COMBUSTION AND QUENCHING OF HYDROCARBON FUEL SPRAYS

Annual Report to

Air Force Office of Scientific Research
Bolling Air Force Base
Washington, DC

by

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A detailed parametric study of the ignition of a monodisperse fuel-air spray in contact with a hot wall was conducted. The theoretical model was one-dimensional unsteady and employed a hybrid Eulerian-Lagrangian numerical scheme. Effects of drop size, chemical kinetics, fuel-air ratios, fuel type and other parameters were examined. The results indicated the statistical character of the spray ignition, the existence of optimum droplet size and optimum fuel-air ratio for the minimum ignition delays. The study was extended to the polydisperse spray. The major conclusion was that the polydisperse results can be correlated with an equivalent monodisperse spray represented by a mean diameter based on the total spray surface area.

The study of ignition for sprays flowing over a hot plate was initiated. The formulation and the numerical coding were completed. Currently the code is being employed to predict the ignition delays for the flowing sprays.

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Preliminary experiments were conducted to investigate the ignition of a single droplet stream along a heated surface. The results show an optimal distance from the surface for the droplet stream. It is speculated that this distance depends on the characteristic evaporation time, diffusion time and convective time inherent to the system. Experiments separating the effects are underway to investigate this interactive process.

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MULTIPLE IGNITION, COMBUSTION AND QUENCHING OF HYDROCARBON FUEL SPRAYS

1 ABSTRACT

A detailed parametric study of the ignition of a monodisperse fuel-air spray in contact with a hot wall was conducted. The theoretical model was one-dimensional unsteady and employed a hybrid Eulerian-Lagrangian numerical scheme. Effects of drop size,chemical kinetics, fuel-air ratios, fuel type and other parameters were examined. The results indicated the statistical character of the spray ignition, the existence of optimum droplet size and optimum fuel-air ratio for the minimum ignition delays. The study was extended to the polydisperse spray. The major conclusion was that the polydisperse results can be correlated with an equivalent monodisperse spray represented by a mean diameter based on the total spray surface area.

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Preliminary experiments were conducted to investigate the ignition of a single droplet stream along a heated surface. The results show an optimal distance from the surface for the droplet stream. It is speculated that this distance depends on the characteristic evaporation time, diffusion time and convective time inherent to the system. Experiments separating the effects are underway to investigate this interactive process.

2 DESCRIPTION OF THE THEORETICAL WORK

The objective of the theoretical efforts is to enhance the understanding of various processes which occur in the ignition of hydrocarbon fuel sprays. The study of the ignition process is also relevant to the flame propagation and quenching phenomena in fuel-air sprays. Another purpose of this study is to develop the capabilities for numerical computations of two-phase flows.

During the last year, a detailed parametric study of the ignition of a monodisperse fuel-air spray in contact with a planar hot wall has been conducted. The theoretical model was one-dimensional unsteady. The numerical computations employed a hybrid Eulerian-Lagrangian scheme. Effects of droplet size, chemical kinetics, overall fuel-air ratio, fuel type and other parameters were examined. Two publications [1,2] have resulted from this study. The results indicate that the spray ignition process has a statistical character. Thus for a given set of parameters, only a range of ignition time delays and ignition energies would be predicted. Another important conclusion of this study was at certain overall fuel-air ratios for certain fuels, the ignition delay time for the sprays could be less than that for the corresponding gaseous mixture. Thus the existence of an optimum droplet size, which increases with fuel volatility and overall fuel-air ratio, was predicted. Similarly the existence of an optimum overall fuel-air ratio which is a function of initial droplet size and fuel volatility was predicted.

The study has been extended to examine the ignition of polydisperse sprays. The results will be presented at the AIAA 23rd Aerospace Sciences Meeting in Reno, Nevada, January 1985. One typical result, shown in Figure 1, indicates that the use of Sauter mean diameter (d_{32}) does not accurately represent the polydisperse sprays for predicting the ignition delays. Instead, the polydisperse results correlate to those for an equivalent monodisperse spray represented by a mean diameter (d_{20}) based on the total spray surface area.

The study of ignition for the flowing sprays over a hot plate was initiated. The formulation of the problem has been completed. A two-dimensional flow of air-fuel spray mixture over a hot plate is considered. The theoretical model is based on an unsteady Lagrangian formulation of liquid-phase properties and an Eulerian representation of gas-phase properties. Initial results would be based on the assumption that self-similar solutions exist for the gas velocity and temperature fields. The liquid-phase properties and the fuel vapor mass fraction fields would be

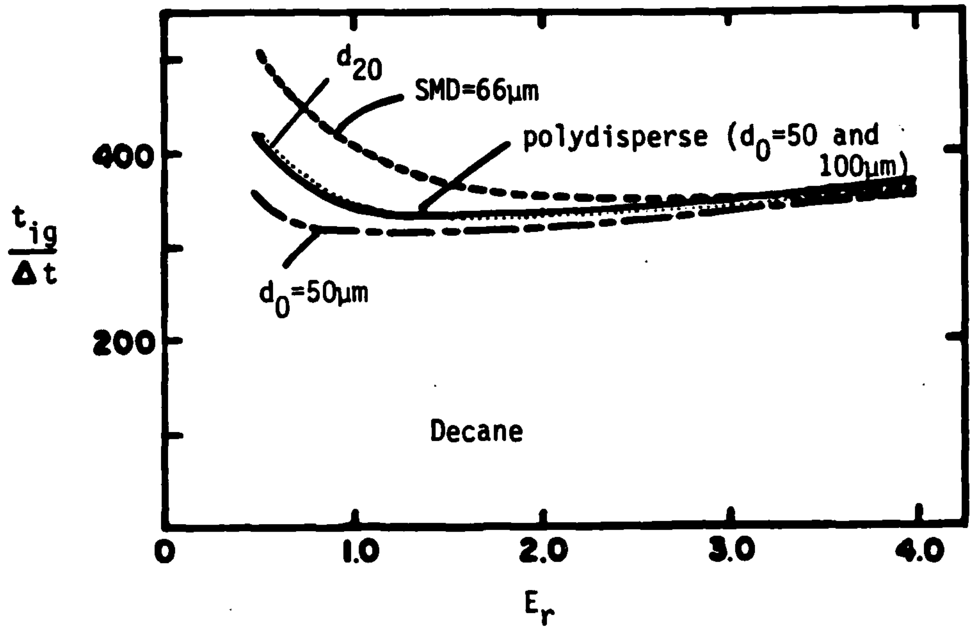

Figure 1: Ignition time delay versus overall equivalence ratio for four different cases (Δt is the temporal step size).

computed by numerically solving the appropriate differential equations. The ignition delays (in terms of the length of the hot surface up to the point of ignition) and the ignition energy would be obtained as a function of various parameters such as the plate temperature, fuel type, overall fuel-air ratio, initial droplet size, initial fuel vapor concentration, and mixture velocity. These results are expected to be obtained during the summer of 1984.

3 DESCRIPTION OF THE EXPERIMENTAL WORK

The objective of this research program is to establish a database on ignition behavior of fuel sprays. An experiment was designed to investigate the role of fuel vapor on the ignition process by controlling the vapor pressure of the air in a laminar fuel mist-air flow. Figure 2 illustrates the experiment set up to establish an air-fuel vapor flow in which monodisperse liquid fuel is sprayed. The fuel vapor concentration is controlled by adjusting the temperature of the air supplied to the apparatus. Heating or cooling the air influences the resulting vapor pressure after this air passed through a series of condensers and is stabilized. A calibration of the apparatus is conducted by sampling the air-vapor flow and gas chromatographic analysis of the mixture to determine the stochiometry of the mixture along the test section.

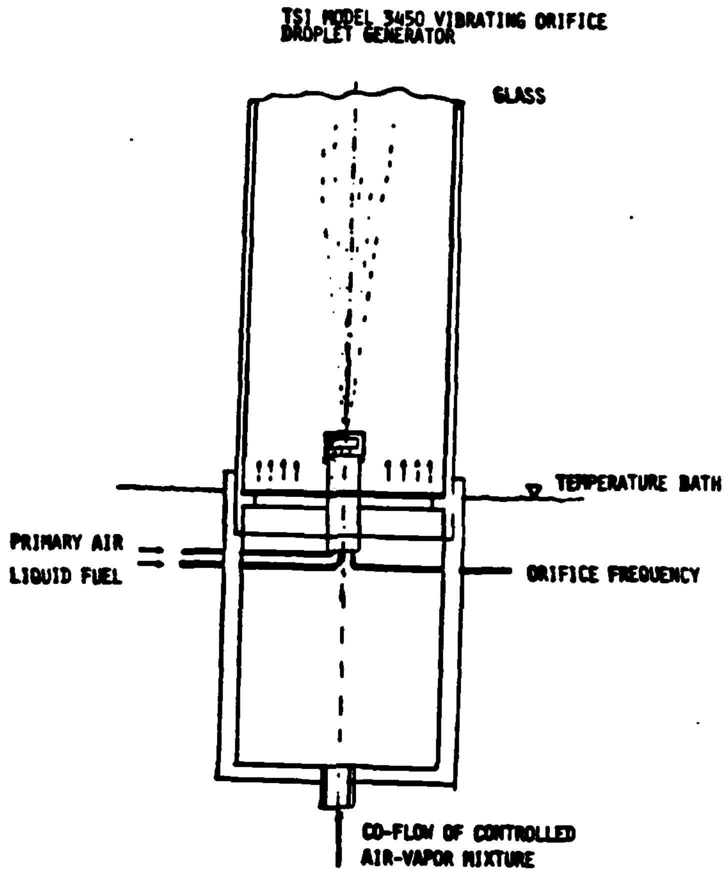

Figure 2: Test section for spray ignition studies in controlled atmosphere.

Experiments will be conducted for varying initial fuel vapor pressure in the air and different droplet sizes of the spray injected. At vapor pressures below saturation pressure the fuel droplets will evaporate at a rate determined by the preset vapor pressure and a stratification of effective vapor pressure along the test section will build up due to droplet evaporation. By controlling the vapor pressure of the air stream entering the test section and the droplet size injected into this air, gas phase stochiometry and droplet size will vary along the column. Positioning the ignition source at various heights above the spray nozzle and sampling the gas phase to determine its stochiometry and measuring the droplet diameter optically or with the impact method, the conditions of two phase mixtures in the vicinity of the ignition source can be determined.

Experiments have been conducted investigating the ignition of a vertical oriented single droplet stream along an electrical heated coil. During this experiment the air was stagnant and not enriched with fuel vapor. This preliminary series of experiments was conducted to gain experience with the droplet generator and to investigate material properties for the hot surface. It was expected that buoyancy will affect the boundary layer in front of the hot surface. High speed Schlieren photography was used to illustrate the thermal boundary layer and the developing flow boundary layer due to natural convection. These experiments were conducted in stagnant air. Analyzing the Schlieren pictures to determine characteristic time and length scales show that, in the case of fast convection, the buoyancy effect on the velocity field in front of the hot surface is in first approximation negligible. However, the flow field is strongly affected down stream behind the hot surface where buoyancy changes the flow characteristics from laminar to turbulent. Due to increased mixing in the thermal wake down stream of the hot plate, a flame establishes itself at this location after ignition takes place in front of the hot surface.

Figure 3 shows the preliminary experimental arrangement used to determine the distance, a, of a single droplet stream from the electrically heated coil surface of temperature, The coil temperature was measured by a chromo-alumel thermocouple and the distance, a, was observed through an alignment microscope with a built-in scale. The droplet stream was set up to pass in parallel along the hot surface penetrating the thermal and natural convection layer formed in front of the heat source. Droplet size is determined from the generator operating conditions (fuel-volume flow, orifice frequency) and the diameter of the vibrating orifice. Adjusting the frequency to avoid satellite droplet formation, the TSI 3050 aerosol generator produces a single stream of monodisperse droplets. The droplet diameter, D_p is calculated from the formula:

$$D_p = \left(\frac{6Q}{\pi f}\right)^{1/3}$$

Q volume flow of liquid set by the syringe pump

f operating frequency of the oscillating

For two droplet diameters a series of tests was conducted to determine the dependency of the surface temperature, T, from the distance to the hot surface of the single droplet stream. Droplet velocity, which determines the characteristic time

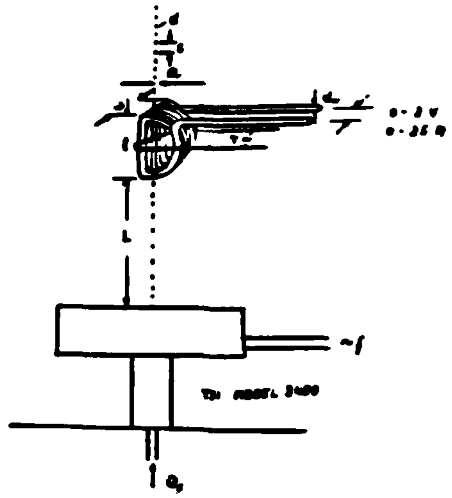

Figure 3: Ignition source: Hot surface dimensions and conditions.

Surface Material: Alumel
1 = 10 mm / 14 mm
d_w = 1 mm
w = 5 mm

Surface temperature measured
with Chromo-Alumel thermocouple

Droplet Dimensions:
Diameter d = 90 μm / 60 μm
Spacing s = 4d
Velocity v = 10 m/s

Fuel : Toluene

the droplets need to pass the heated surface, was predicted from particle generator conditions and solving the momentum equation for a sphere moving opposite of gravity under drag influence. Measurements of the droplet velocity using double-flash photography were performed. On the average, a velocity of 3 m/s was observed providing a residence time of 50 μsec for the droplet in front of the heated surface.

The first set of experiments was conducted to determine the ignition distance of the droplet stream from the heated surface at varying surface temperatures. The droplet string was positioned in front of the hot surface and a stable surface temperature was established. By moving the heated surface closer to the droplets the distance between surface and droplet stream was obtained. Small fluctuations of the stream location of the order of the droplet diameter relative to the heated surface complicated the measurements.

In Figure 4 preliminary results are presented for two droplet diameters. The following observations were made:

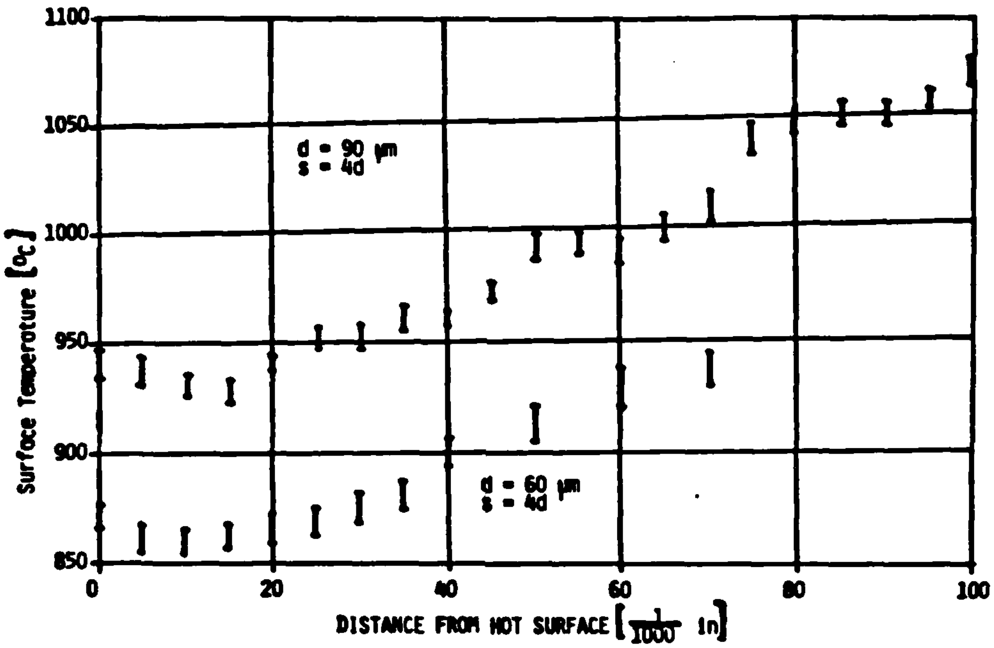

Figure 4: Hot surface temperature as function of single droplet stream distance for ignition of stream.

There seems to exist an optimum "ignition distance" for given droplet size and flow conditions. This distance is an outcome of balancing evaporation time and travel time along the hot surface or in the thermal boundary layer set up by the heated surface. If the droplet stream is too close to the surface, evaporation occurs fast, establishing a local fuel-rich environment. This would increase the necessary ignition energy of the fuel vapor reflected in a higher surface temperature. The optimum distance for 90 μm droplets seems to establish itself at 15/1000 in. and 925°C.

At this location the heat transfer to the droplets was consistent with the fly-by-time igniting the droplet stream. Smaller droplets need less surface temperature for ignition. The minimum surface temperature for 60 μm droplets was 865°C at about 10/1000 in. away from the surface.

Since too many disturbing affects might contribute to misinterpretation of this preliminary result, more detailed experiments are suggested to investigate, for example, the influence of surface orientation with respect to gravity, velocity of the droplets and surface radiation conditions.

In Figure 5 sequences of a high speed motion picture under Schlieren conditions on the left, and a direct image of the ignited droplet stream on the right, are shown.

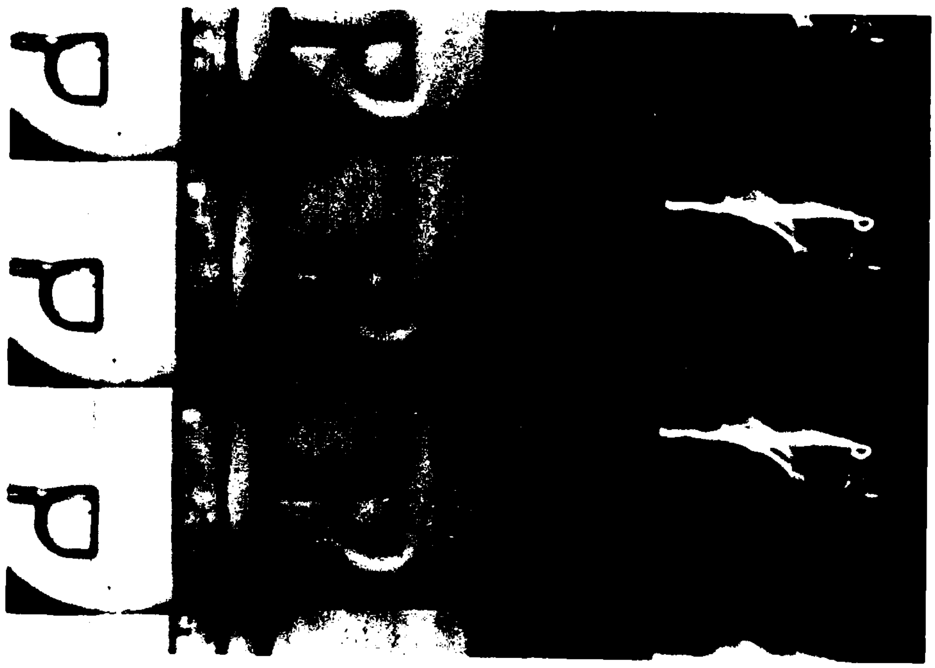

Figure 5: Burning toluene single droplet stream (right) and sequence of high speed Schlieren movie illustrating the buoyancy dominated thermal boundary layer without flame (center) and with flame (left).

The thermal boundary layer is visible in Schlieren mode. The dark area above the heating coil is the shadow of the sooting flame (visible in the far left sequence). High speed photography is a powerful tool to analyze the time scales involved in the process.

Figure 6 illustrates the difficulties encountered in igniting a spray in a controlled way. A high intensity light flash was used to freeze the droplets in time (lower part of the pictures) whereas the time integrated image of the spray flame stabilizes itself in the hot buoyant wake above the heated coil.

Figure 6: Spray burning in thermal wake of heat source after ignition.

4 LIST OF PUBLICATIONS PRODUCED THROUGH THIS RESEARCH GRANT

1. S.K. Aggarwal and W.A. Sirignano, "Ignition of Air-Fuel Spray Mixtures by Hot Surfaces", Fall Technical Meeting, Eastern Section Meeting/Combustion Institute, Providence, RI, November 8-10, 1983.

2. S.K. Aggarwal and W.A. Sirignano, "Ignition of Fuel Sprays: Deterministic Calculations for Idealized Droplet Arrays", Twentieth (International) Symposium on Combustion, Univ. of Michigan, Ann Arbor, August 12-17, 1984.

3. S.K. Aggarwal and W.A. Sirignano, "On the use of Sauter Mean Diameter in the Ignition Study of Polydisperse Sprays", submitted for presentation at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14-17, 1985.

Copies of these papers are attached.

5 PERSONNEL INVOLVED IN THIS RESEARCH PROGRAM

Suresh Aggarwal, post doctoral senior research engineer, PhD in Mechanical Engineering, Georgia Institute of Technology 1978.

Roger Bishop, graduate student in Master of Engineering Program, BS in Mechanical Engineering, CMU 1892. Experimental part of the project.

Mark Pleskow, engineering technician, BS in Civil Engineering, CMU 1982.

William A. Sirignano, professor, co-principal investigator, PhD in Mechanical Engineering, Princeton University 1964.

Holger T. Sommer, assistant professor, cop-principal investigator, PhD in Mechanical Engineering, RWTH Aachen, West Germany 1979.

6 INTERACTION WITH OTHER RESEARCH GROUPS

Professor Sirignano spent two summer months in 1984 at the Combustion Facility, Sandia Laboratories, Livermore, CA and discussed details of this project with Drs. Allen Kerstein and William Sanders. He also presented the recent results to Professor Oppenheim of the University of California, Berkeley and Professor Paul Clavin who was visiting from France.

Professor Sommer discussed experimental difficulties with Professor S.C. Yao of CMU.

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